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Shelley, J.S.; LeClaire, R.; Miracle, D.; Nichols, J., "Yes – This is Rocket Science: MMCs for Liquid Rocket Engines"

The Metal Society, Fall Meeting **(Statement A)**
(Indianapolis, IN, 01 September 2001) (Deadline: 15 June 2001)

Yes – This is Rocket Science:

MMCs for Liquid Rocket Engines

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Summary

The Air Force's Integrated High-Payoff Rocket Propulsion Technologies (IHPRPT) Program has established aggressive goals for both improved performance and reduced cost of rocket engines and components. Achieving these goals relies on developing affordable Metal Matrix Composite (MMC) technologies for application to Liquid Rocket Engines (LREs). Efforts are being conducted on three types of MMCs: Aluminum, Copper, and Nickel matrix material systems. Potential applications include turbopump housings, rotating machinery, and high stiffness flanges and ductwork. This article will address affordability goals, and review the IHPRPT goals as well as the current material requirements for MMC technologies being developed for application to LREs.

Introduction

Contrary to popular belief, *Rocket Science* is not difficult. It is, however, full of extremes. Rocket Propulsion is the X-games of technologies. For example, operational mission lives are extremely short, lasting less than 10 minutes. Yet, low cycle fatigue environments in rotating turbomachinery are life limiting. Launch costs are extremely high, measured in billions of dollars, yet engine acquisition costs are measured in the tens of thousands. Turbopumps that can pump an Olympic-size swimming pool dry in under 3 minutes are less than 42 inches long and weigh less than 4000 lbs.[1] Temperatures in these turbopumps span the extremes from the –253°C of liquid hydrogen to the 3300°C of propellant combustion gases. With power densities in the pumps 10 times greater than those in jet aircraft engines,[2] pump speeds

add of for consistency

force materials to operate close to yield points. The full-flow engine cycle requires that turbine components survive these stress states in high temperature, high pressure, oxygen-rich steam. Finally, while ignition transients last for only fractions of minutes, low cycle fatigue deflections in nozzle exit cones can be greater than 5% due to side loads during ignition. Designing components to survive these extremes is essential to creating and controlling the enormous energy required to put a vehicle into orbit. Building liquid rocket engines that do that job efficiently and reliably is what makes rocket propulsion *Rocket Science.*

Metal matrix composites are maturing to the point that they are applicable to rocket propulsion.[3] The good mix of properties and ability to tailor properties make MMC attractive for liquid rocket engine applications. High specific strengths help reduce the weight of components while enabling design modifications for better performance. Higher, and lower, temperature capability materials improve engine performance and increase reliability. Improved stiffness while maintaining weldability and bearing strength for bolted joints reduces flange weight and fatigue loads. Near-net shape process technologies reduce acquisition costs and lead times. Developing MMCs for rocket applications, providing insertion opportunities, and tracking engine-level payoffs of materials technologies is the job of the Materials Working Group (IMWG) of the Integrated High Payoff Rocket Propulsion Technologies program (IHPRPT).

IHPRPT and IMWG

The Integrated High Performance Rocket Propulsion Technology Program (IHPRPT) began in 1994 as a means of coordinating technology development for rocket propulsion between the services and providing demonstrations of performance goals at an engine level. It is a joint DOD, NASA, and industry effort, managed by the Air Force Research Laboratory, and divided into three phases of engine 2000 2005 improvement. Each phase culminates in an engine demonstration, nominally scheduled for 2002, 2007, and 2010. The first phase demonstration engine has begun component testing. This engine is attempting to demonstrate the IHPRPT goals by implementing an engineering design change from the fuel-rich staged combustion cycle used by the Space Shuttle Main Engine (SSME) to the full-flow staged combustion cycle. No new materials developments were inserted into this demonstration. IHPRPT has established engine-

level goals for improvement and IMWG coordinates the materials activities necessary to achieving those goals. When the importance of new materials insertion efforts to achieving IHPRPT goals was realized, the materials working group (IMWG) was establish in 1997.

Engine-level improvements can be characterized in several ways: performance, cost, reliability, and maintainability. While the Air Force mission is mostly expendable, the drive toward "aircraft-Like operations" impels the need for reusable engine technologies. Therefore, maintainability goals for mean time between replacement and refurbishment costs have been established under IHPRPT. Advancements can be measured by improved thrust-to-weight (or increased specific impulse - thrust achieved divided by weight flow rate of propellant consumed), increased reliability, and decreased cost. In the past, these areas have been inextricably connected in that advancing one area has typically involved compromises in the other two areas. An optimum advancement would allow a simultaneous increase in performance, reliability, and a decrease in cost. It is a goal of the IHPRPT program to achieve just such simultaneous and optimum advancements.

IHPRPT phase II goals are to be demonstrated through component-level tests in 2005. Some of the goals to be demonstrated are a thrust-to-weight increase of 60%, cost reduction of 25%, and a Mean Time Between Replacement (MTBR) of 60 missions. These overall goals are broken down into component-level objectives for weight reduction and increased performance. Approaches to meet objectives combine evolutionary engineering improvements, engineering design changes, and advanced materials insertion. Materials technologies can influence both evolutionary design improvements and enable new engine technologies. Evolutionary improvements include reducing the weight of ducting, bellows, and flanges, improving the performance of cryogenic fuel pumps, and decreasing the weight of nozzle and exit cone structures. Two new concepts need materials and process technologies advancements to be implemented before they can be fully developed. The full-flow engine cycle and transpiration cooling concepts have existed as design concepts for years, but these engineering technologies require high temperature oxidation resistant materials and finely controlled porous materials, respectively, to enable their demonstration.

Affordability for Liquid Rocket Engines

As with the other extremes in rocket propulsion, the term "affordable" takes on an extreme definition in an industry that counts a single operation in the billions of dollars. Engine acquisition costs are weighed against multi-million dollar operations costs. Lead times for launch opportunities can be years and engine production rates are in the single digits per year. When payloads are unique, or human lives, reliability is nearly priceless. For these reasons, what is affordable for the rocket propulsion industry is extreme in other circumstances.

In 1999, General motors produced 8.6 million automobile engines, a production rate of nearly 18 engines/minute. With that high a production rate, manufacturing processes are fast and must manage large throughput. At a cost of about $5000/engine, development costs are on the order of $2/engine and the costs are spread over a customer base in 190 countries.[4] With the current price of new cars, the engine costs about 30% of the vehicle costs. Similarly, jet aircraft powerplants cost roughly 36% of the vehicle costs. F-15 fighters are powered by two F-100 engines produced by Pratt and Whitney and each costing approximately 18% of the total vehicle cost. Pratt and Whitney produces the F-100 engine at a rate of about 250/year and development costs of major upgrades are spread over several thousand engines.[5] Since production rates are lower for jet aircraft engines than for automobiles, power density requirements are two orders of magnitude higher, and reliability is more difficult to achieve, affordable costs for jet engines are higher than for automobile engines. Production methods tend to be lower rate, but with much tighter tolerances and less variability than for automobile engines. For rocket engines, production rates are extremely low and scrap rates are acceptable at high levels, sometimes as much as 50%. While Meisl concludes in his comparison of jet aircraft and rocket engines that, when corrected for the difference in production quantities, the costs of jet engines and liquid rocket engines are comparable,[2] the production quantity is the difference. Currently, the Space Shuttle Main Engine is produced at a rate of less than one per year. However, the cost of a single SSME is only approximately 5% of the total vehicle cost. (Keep in mind that there are 3 SSMEs on each Shuttle, and the propulsion system includes two solid rocket boosters. All together, the total shuttle propulsion system costs about 30% of the vehicle.) Development costs have been amortized over only approximately 100 engines. With these extremely low production rates and quantity produced, more expensive and slower manufacturing techniques are affordable. The economies of scale that make large capital investments affordable to increase throughput of automobile engines can not – "cannot" is one word

be achieved by rocket engine industry. However, technology investments that increase performance and reliability are affordable as long as they are cost competitive with system costs.

It is within this framework of affordability that IMWG and IHPRPT are developing metal matrix composites technologies for liquid rocket engines. The following section will discuss the individual goals of specific ongoing efforts. However, in summary, most of the current metal matrix composite efforts for liquid rocket propulsion are working to achieve acceptable strength to weight ratios while maintaining sufficient ductility for low cycle fatigue resistance and joint compatibility. Specialized requirements, such as compatibility with high-temperature, oxygen-rich steam for the full-flow engine cycle[6] are also being considered.

Aluminum Metal Matrix Composites

Al MMCs, both particulate and chopped fiber reinforced, are probably the most mature of the MMC technologies being developed for rocket propulsion. The potential for application of these material systems to other industries, such as the automotive, aircraft, and sporting goods industries are also making these technologies the most affordable to develop. The rocket industry is turning to Al MMCs primarily to reduce weight of structural components. The potential applications of Al MMCs are numerous throughout the engine, but basically fall into three categories: stiffness driven components, "warm" temperature applications, and cryogenic applications. Stiffness driven components include flanges, thrust chamber jackets, and support structures. These components transfer loads from one structure to another through welded, bonded, and bolted joints. While not in direct contact with either hot combustion products or cryogenic propellants, these components tend to operate in moderate thermal and chemical environments. Current systems use nickel-based superalloys in these applications for both high stiffness and compatibility with mating surfaces. The driving parameters for materials for use in these applications are high stiffness (moduli greater than 220 GPa (32 ksi) are desired), weld or braze-ability, physical compatibility with dissimilar materials, and bearing strength in bolted joints. Near-net shape processing techniques that are capable of fabricating generally axisymmetric shapes with multiple radii of curvature are necessary. Secondary thermal processes such as brazing and welding are commonly used during subassembly fabrication. MMCs with inserts and mixed reinforcement types (particulate, chopped fiber, and continuous

fiber) are desired for these applications to functionally grade a welded interface to a stiff bolted joint. Methods of joining MMCs and dissimilar materials also require development.

"Warm" temperature applications for aluminum MMCs are considered high temperature applications for aluminum, but moderate temperature environments in rocket engines. Turbine rotating components, stationary elements, and housings in expander cycle engines run at temperatures up to 260 °C (500 °F). "Warm" propellant ducting and backup structures also operate in this thermal environment, but at lower stress levels. Rotating machinery has the most severe requirements in this area with the material strength requirements for single stage pump designs pushing 862 MPa (125 ksi). These components are directly exposed to (usually) hydrogen-rich turbine drive gases and require both creep and fatigue resistance. Nickel-based superalloys are currently used for these components. There is a desire to move away from expensive machining of forged billets for these components, however, extremely complex shapes with good surface finishes are required.

Complex shapes with smooth interior surfaces are also needed for cryogenic pump components. Housings, inducers, impellers, and stationary guide vanes must operate at the -244 °C (-423 °F) temperature of liquid hydrogen. Meticulous design practices are employed to account for varying shrinkage between components during cool down to maintain tight tolerances and carefully engineered flow paths. Hydrogen compatibility is required along with fatigue resistance. Forged and machined titanium alloys are currently used for these components because of their good properties at low temperatures. Strengths in the range of 675 MPa (100 ksi), ductilities greater than 6%, and fatigue limits greater than 275 MPa (40 ksi) at temperature with densities less than 4 g/cm^3 (0.14 lb/in^3) are desired to improve on the performance of the current Ti alloys. Low, or controllable, CTEs would allow greater design flexibility. As with other components, near net-shape processing techniques are desired to alleviate the reliance on expensive, and long lead time, forging and machining processes.

Recent efforts by the rocket community to develop aluminum materials for component applications have centered on manufacturing "nanophase" monolithic aluminum alloys. At this time, a "nanophase" alloy composition has not been optimized; however an aluminum-magnesium alloy that maintains a grain size on the order of 10 nm has been developed. Process variables ranging from efficiency of powder attrition to large-mechanical-work-input fabrication techniques are being developed. Current Al

MMC material and process development efforts are exploring near-net shape casting techniques, joining to dissimilar metals, preforming techniques aimed at increasing final composite ductility, and functionally grading properties by selective control of preform density. Both particulate and chopped fiber reinforced Al MMCs are currently being investigated and strengths as high as 620 MPa (90 ksi) have been achieved in particulate reinforced systems.

Copper Metal Matrix Composites

The development of Cu MMCs, in the past, has been plagued by CTE incompatibility between matrix and filler, delamination, and matrix infiltration issues. Because of the uniqueness of the applications of Cu MMCs, this technology has been slower to develop and requires greater investment than Al MMC technology. The two properties of copper which make it attractive as a matrix material for rocket engine components are its oxygen compatibility and high thermal conductivity. Oxygen compatibility is essential for turbopump hardware that is powered by high-temperature, oxygen-rich steam in the full-flow engine cycle. In the full flow cycle, the oxygen turbopump housing and ducts will be in direct contact with high-temperature oxygen-rich steam. These applications require strength at temperature and creep resistance as well as oxygen compatibility. To be considered for use in an oxygen-rich environment, a material must not support combustion at 69 MPa (10,000 psi) oxygen, and cannot be susceptible to ignition by impact of a 1.5 mm (0.06 in) diameter aluminum particulate in a supersonic stream of oxygen.[7] Operating conditions can be varied to account for material capabilities, but strengths of 413 MPa (60 ksi) are required at 260 °C (500 °F) with densities less than 7.5 g/cm^3 (0.27 lbs/in^3) for some applications. As with Al MMCs, near-net shape processing techniques that create good surface finishes with little machining require development.

Heat conduction applications are primarily thrust chamber liners, either regeneratively cooled or transpiration cooled. While most regenerative cooling schemes require the high conductivity of monolithic copper, increased strength, creep, and fatigue resistance are needed to overcome deformation due to thermal cycling stresses. The thrust chamber liner is exposed the to ? 20 MPa (3000 psi) combustion gases on the inner surface and cryogenic propellants on the outer surface where it mates with the structural jacket. Thermal fatigue from transients of thousands of degrees in fluid temperature during engine start up and shut down is a problem with current copper systems. The exact material requirements depend on the thrust

chamber design. However, the high heat transfer rates required to cool the combustion chamber liner have precluded use of copper matrix composites in the past.

Nickel Metal Matrix Composites and other Materials

The primary driver for development of nickel based MMCs is the hot oxygen-rich steam environment of the full flow cycle engine. This technology is in its infancy, however lessons learned from Al MMC technologies will help defray development time and cost. Turbine components require high strength, creep and fatigue resistance at temperature along with oxygen compatibility and corrosion resistance. Nickel-based superalloys are the materials of choice for these components in systems currently under development. While increased strength, stiffness, and creep resistance may be achieved by creating composites with SiC particles or fibers, oxygen compatibility cannot be compromised for components in the oxygen-rich drive gas environment of the full-flow cycle engine. As stated in the section on copper MMCs, to be considered for use in an oxygen-rich environment, a material must not support combustion at 69 MPa (10,000 psi) oxygen and can not be susceptible to ignition by impact of a 1.5 mm (0.06 in) aluminum particulate in a supersonic oxygen stream.[7] Thermal shock environments during the engine start transients preclude the use of coated material systems for turbine blade applications, at this time. Therefore, the entire bulk of a turbine blade material must be resistant to the oxygen-rich combustion product environment. Turbine blades and disks are typically uncooled for their roughly 9 minute operational cycle. So, short operational periods were bulk material temperatures reach 730 °C (1200 °F) are not uncommon. Strengths greater than 1040 MPa (150 ksi) at temperature are desirable with material densities less than 6.5 g/m^3 (0.23 lb/in^3) for some designs. These stress, temperature, and chemical environments are severe and increasing MTBR goals make these material property goals even more strenuous to achieve.

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here"

Other non-rotating component must also survive extreme operating environments. Injector faceplates, bodies, and preburners require oxidation resistance, corrosion resistance, and hydrogen embrittlement resistance at high temperature. Injectors meter and direct the flow of propellants into the main combustion chamber. Preburners are the small combustion chambers in which the turbine drive gas is generated. Current systems, some of which are actively cooled, use cobalt alloys for these components.

Extreme thermal environments (gas temperatures approaching 918 °C (1500 °F)) and pressures up to 62 MPa (9 ksi) are projected for these components in future engines. Monolithic silicon nitride is being applied to the injector body, but the difficulty of mating the ceramic body to a metallic thrust chamber has not been overcome to permit testing of this ceramic injector. Because of the generally axisymmetric shape of the injector body, continuous fiber composites have been suggested for this application, however, component mating requirements create challenges for continuous fiber composites.

Currently funded efforts are working to improve the oxygen compatibility and strength of monolithic nickel-based superalloys and an improved stressed-oxidation response has been demonstrated. Nickel MMCs show great promise for application to rocket components, but the materials, process, and design technologies are considered to be too immature for component demonstration at this time. Material and process development efforts in this area are being planned for funding within two to three years.

Conclusion

MMCs are considered mid-term material solutions to rocket component needs. The potential to spread development costs over several industries make MMC technologies affordable to develop. The potential to tailor specific properties and produce near-net shape components with small capital investment promises to make MMC fabrication technologies affordable for the extremely low production rates of rocket engine components. On the current IHPRPT roadmaps, components employing MMCs should be demonstrated in 2005 with advances continuing through 2010. In the far term, weight and turbine inlet temperature goals may force the community away from metallic materials and toward ceramic and CMC material systems. Thermal and environmental coatings technologies will also require development. However, ductility requirements, geometric constraints, and environment compatibility needs in rocket engines ensure that metal matrix composites will play an important role in rocket technology development for the foreseeable future.

Engine

[1] NASA Facts Sheet

[2] Meisl, C.J., Rocket Engine Vs. Jet Engine Comparison, AIAA 92-3686, July 1992, AIAA.

[3] Miracle, D.B., and Maruyama, ?

[4] (Information from Motortrend web press releases, the GM website, and my local gm dealer.) GM

[5] (Information from the Pratt and Whitney website and Edwards AFB Public Affairs office.)

incomplete reference, please fix

[6] Shelley, J.S., LeClaire, R. and Nichols, J., Journal of Metals, May 01.
[7] H.D. Beeson, W.F. Stewart, and S.S. Woods, “Safe Use of Oxygen and Oxygen Systems”, ASTM, stock number MNL36 (2000); and ASTM G 125.

YES - This is Rocket Science:
MMCs for Liquid Rocket Engines

04-08 Nov 01

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Overview

- What is Affordable for Liquid Rocket Propulsion?
- Affordability goals and IHPRPT
- IHPRPT Phase II Technologies
- MMC projects for IHPRPT Phase II
- Summary

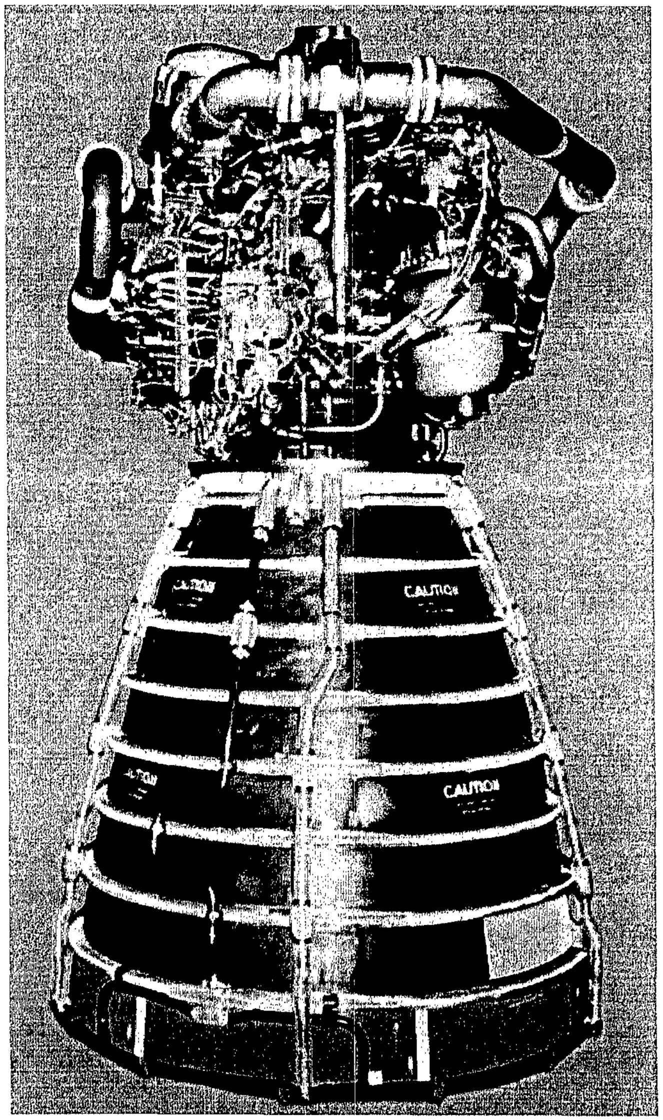
What is Affordable?

- Placing satellites in orbit is expensive
  - satellites can cost [$1B]
  - launch costs [$2B] (including vehicle)
- Most vehicles have multiple liquid rocket engines
  - STS has 3 SSMEs/vehicle
  - Reliability is a necessity
- Engine costs less than 5% of total vehicle costs
  - [$20-50M]

What is Affordable?

- Low production rates
  - 1 SSME produced per year, approx 100 total
    - 3 major upgrades since 1980 (1988, 1995, 1999)
      - Over 6400 P&W F100 engines produced and in-service since 1974 in 3 models, 250/year
        - engine development cycle roughly 10-12 years
      - In 1996, US auto makers produced 11.8 M cars
        - new model development cycle 3-5 years
- Highly specific sub-components designs
  - few modular parts
  - labor-intensive assembly, refurbishment
- Performance, reliability cannot be sacrificed

Space Shuttle Main Engine



Thrust	470,000 lbf
Weight	7,289 lb
Mission Duration	9 minutes
MTBO	7.5 hrs

Designed to 10 mission MTBR

105 in diam by 167 in long

3 SSMEs on Space Shuttle

What is Affordable?

housings are 75% of turbopump wt

- Most turbomachinery components machined from forged billets of Ni alloys
  - 51% total engine weight, 42% total engine cost
  - high performance properties with low Cv, tight tolerances

check this # includes rotating components

- Thrust chamber jacket Electrodeposited Nickel
  - 18% of C&ECD weight, 6.6% engine weight
  - 28% of C&ECD cost, 11% engine cost
  - 6 months to 1.5 year lead time
  - optimize shape, maximize liner/jacket bond integrity

Affordability Goals

- Integrated high ~~Performance~~ Payoff Rocket Propulsion Technology Program (IHPRPT) has established goals based on total system affordability
  - Engine performance
  - Reusability, Reliability
  - Engine cost

- System level goals flowed down to component level goals
  - component goals can be traded off

IHPRPT

- Integrated High-Payoff Rocket Propulsion Technology program
  - framework for guiding and tracking performance improvements
  - DoD and NASA, headed by Air Force, 1995
  - materials requirements tracked through IMWG (IHPRPT Materials Working Group), 1997
  - 5 years into a 15 year program
    - 3 phases planned, 5 years each
    - each phase culminates in an engine demonstration

IHPRPT Goals

Cryogenic Boost and Orbit Transfer

	Phase I	Phase II	Phase III
Reduce Stage Failure Rate	25%	50%	75%
Improve I_{sp} (sec)	1%	2%	3%
Reduce Hardware Costs	15%	25%	35%
Reduce Support Costs	15%	25%	35%
Improve Thrust to Weight	30%	60%	100%
Mean Time Between Removal (Mission Life-Reusable)	20	40	100

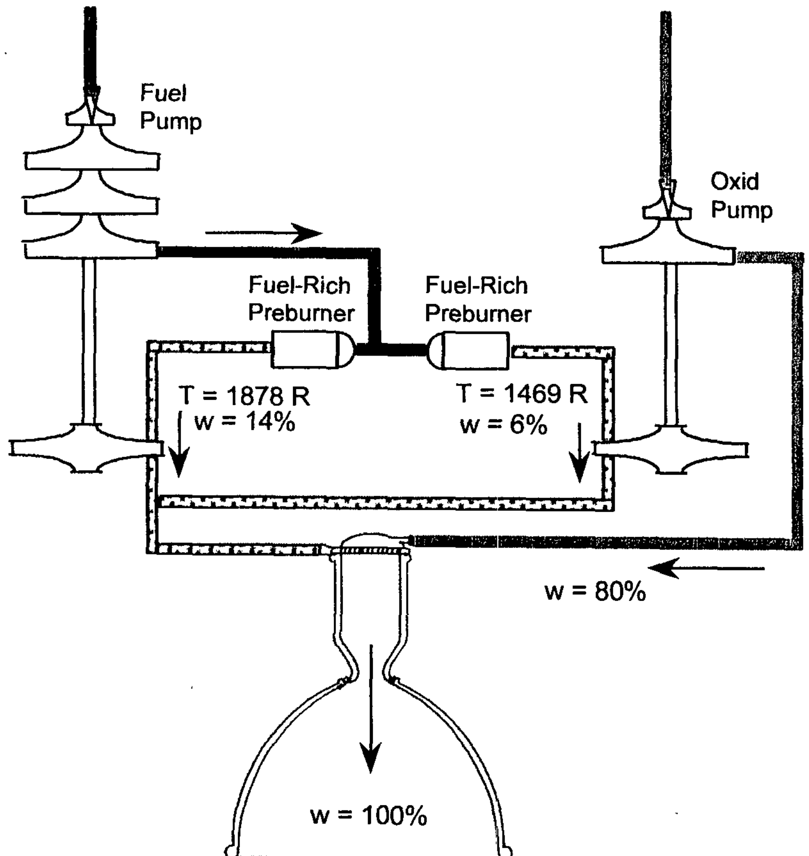
Materials Roles in IHPRPT Goals

- Attack thrust-to-weight, hardware cost, MTBR, and refurbishment cost goals directly through materials substitutions
  - -lighter weight, lower cost materials and processes

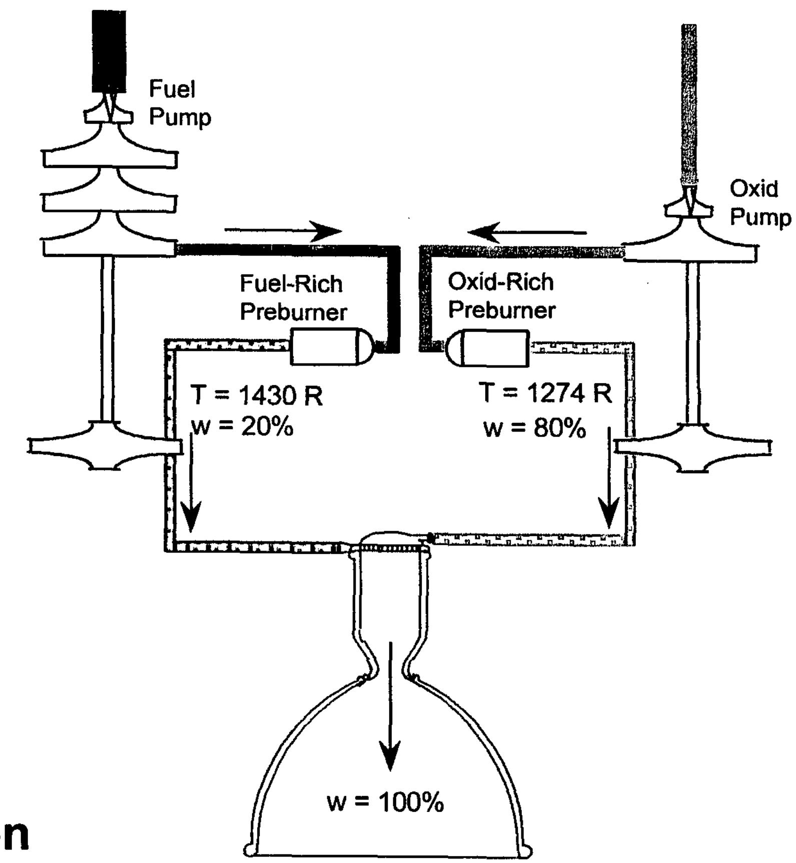
- Enable engineering design changes
  - full-flow engine cycle (closed)
  - reduced number of pump stages
  - increased combustion pressures
  - lighter, higher area ratio nozzles

Full Flow Cycle

Staged Combustion Cycle (SSME)

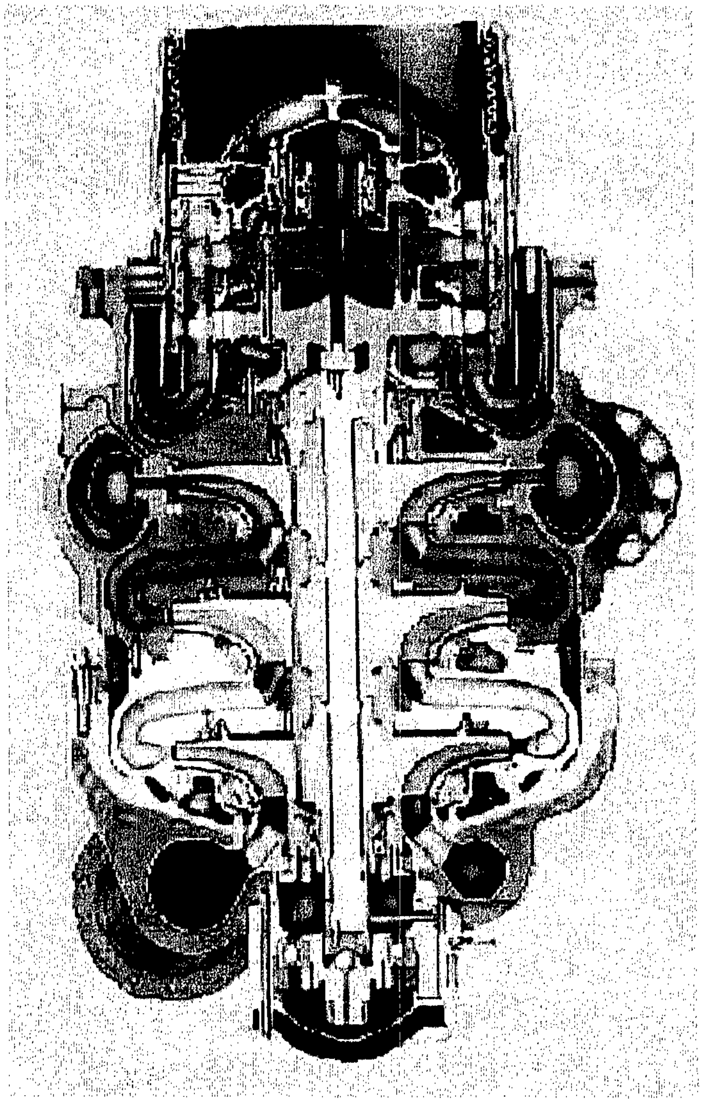


Full Flow Staged Combustion Cycle



hydrogen
oxygen

SSME HPFTP



High Pressure Fuel Turbopump

- 75,000 Horsepower
- 178 lbs/sec fuel flow rate
- 6,900 psia discharge pressure
- 1,440 °F turbine temperature
- 37,000 rpm
- 3 stage pump/2 stage turbine
- 480 lbs (218 kg)
- roughly 30 in diam by 41 in long

Materials Approaches for Turbopumps

- Reduce weight over current nickel superalloys
  - substitute particulate reinforced Al MMCs in LH_2
  - develop higher specific strength Ni alloys for O_2
- Reduce production costs over forged and machined
  - cast and near net shape process
- Develop high strength, tough materials
  - low volume fraction AlO_2 reinforced Al MMC
  - chopped fiber Al MMC, and "functionally graded"
  - control Ni superalloy composition to balance strength and Ox compatibility

Materials Requirements for Pumps

- High strength at cryogenic temperatures (125 ksi)
- Low density (0.14 lb/in^2, 3.9 g/cc^3)
- LCF resistance and toughness at cryogenic temperatures
- Environmental compatibility
  - HE resistance
  - oxygen compatibility
- Amenable to deterministic design methods
  - generally requires ductility above 6% at temperature

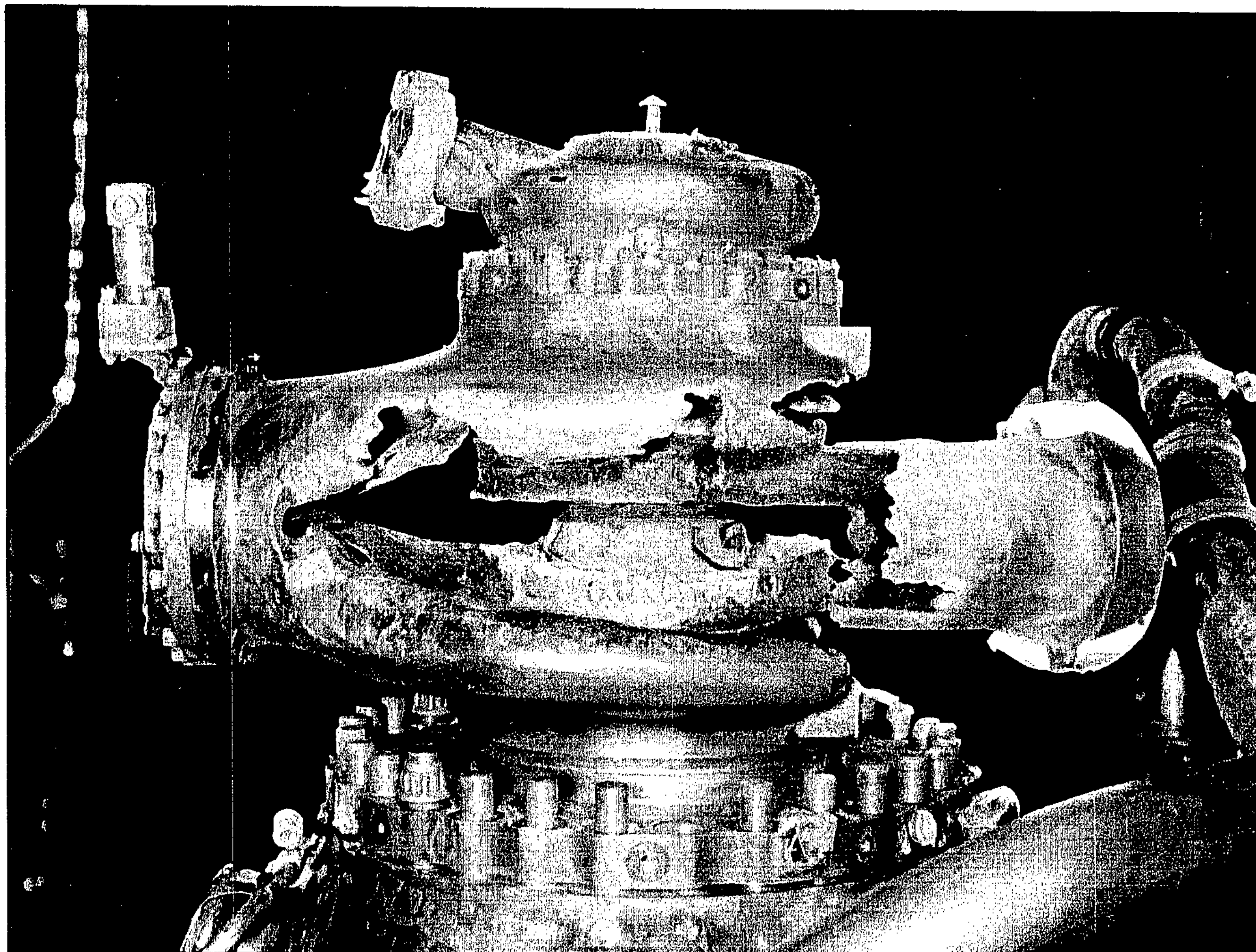
Challenges

- Control of reinforcement volume fraction
  - high strength = high loading
  - ductility and toughness = low loading
  - preforms prefer moderate loadings (20 - 50%)
  - different reinforcement geometries require different matrix alloys
- Near-net shape processing of complex geometries
  - tight tolerances
  - hydrodynamically smooth interior surfaces
- Oxygen Compatability

Materials Requirements for Full Flow Cycle

- Oxygen Compatibility
  - 6000 psi, 1000 deg F ox-rich steam (92 mol% O_2)
- High strength at temperature
  - 175 ksi at 850 deg F
- Creep resistant

Most High Strength Alloys Burn in High Pressure GOX

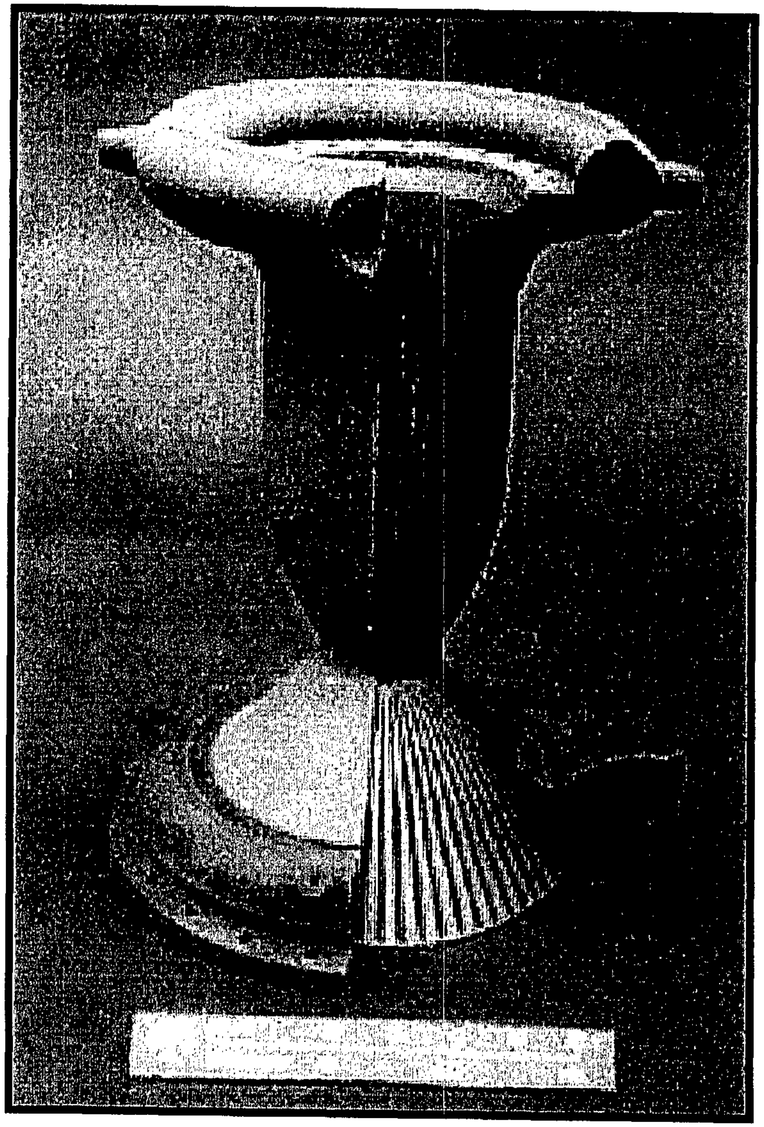


From Cliff Bampton, Boeing - Rocketdyne

Current Pump Projects

- Housings
  - particulate reinforced aluminum
    - 20 - 40% projected weight savings, moderate risk, MRL = 3.5, PRL = 3
  - chopped fiber reinforced aluminum
    - 20 - 40 % -ΔW, mod risk, MRL = 2.5, PRL = 2
- Rotating components
  - high-strength, Ox compatible alloys
    - 10 - 20% -ΔW, mod-high risk, MRL = 2, PRL = 5
  - ‘nanostructured’ Al
    - 0 - 10% -ΔW, mod-high risk, MRL = 2.5, PRL = 1

Typical Combustion Chamber



- Injector attaches at top
- Flow is from top to bottom
- Hot gas wall is copper alloy
- Structural Jacket and manifolds are high strength steel or nickel alloy
- Coolant channels contain high pressure (7000 psi) fuel (LH2)

Materials Approaches for Thrust Chambers and Nozzles

- Reduce weight and production costs over ED nickel
  - cast particulate Al MMC over regeneratively cooled copper liner
  - examine applicability of CMCs, continuous fiber MMCs and C/C
- Enable efficient transpiration cooling
  - foam liner

Challenges

- Bonding to copper liners
  - eutectic forms
  - CTE mismatch and thermal cycling
  - HE
- Controlling Porosity
- Manifolding and attachments
  - joining and co-processing methods not well-developed
- Limited design experience with continuous fiber composites

Current Transpiration Cooling Projects

- Design optimization
  - analytical modeling and simulation effort
- Process and Fabrication efforts
  - "cool wall" copper liner
    - MRL = 4, PRL = 4, TRL = 2
  - "hot wall" concept
    - MRL = 1, PRL = 1, TRL = 1
- Future Efforts
  - small article demonstration testing

Current Projects for Nozzles

- Exploratory effort for erosion-resistant high-temperature materials
  - environmental protective coatings
- Future Efforts
  - engineering design trade studies
    - potential expendable exit cone development
    - materials for high-stiffness nozzle concepts

Summary

- Materials development efforts are essential to achieving IHPRPT Phase II and III goals
  - engine system goals for performance, reliability, and cost
    - direct effects
    - enable design changes
- Affordability is based on low production rate, high reliability, specialized components
- MMC technologies can help achieve goals

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Backup slides

MRLs and PRLs

- Creates a framework for judging material readiness for a particular application
  - application (component) specific
  - time frame specific
- Establishes uniform demonstration goals for material development and insertion
  - no specific route of progression implied
  - no assessment of degree of difficulty of progression

Aerospace Corp MRL and PRL

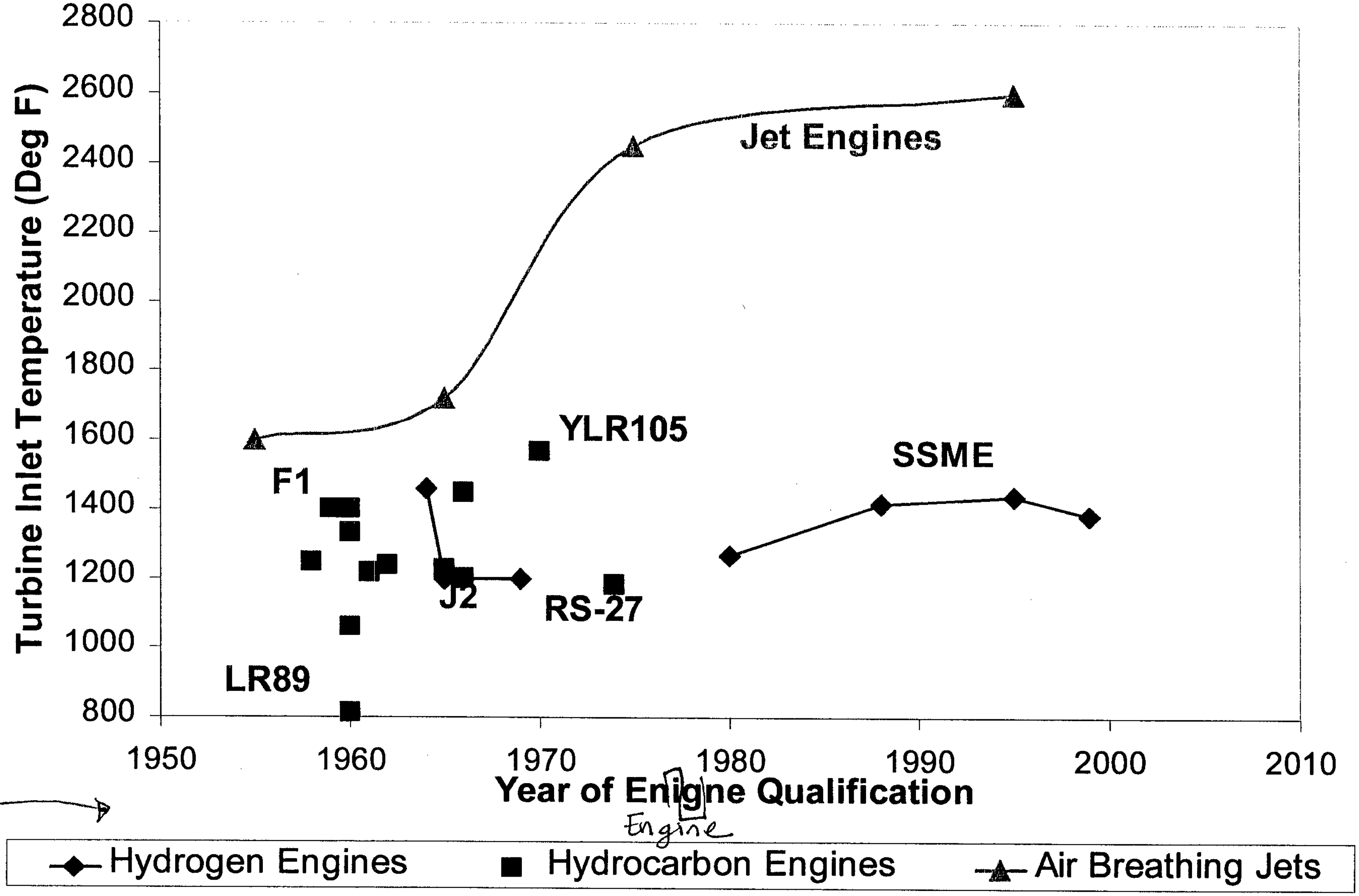
DEFINITIONS

Materials Readiness Level (MRL)	Level	Process Readiness Level (PRL)
Material routinely available and used in similar components	6	Process applied to object has produced defect free components; process parameter ranges identified
Material applied to shapes of the size and type of objective component with verified properties	5	Process has been applied to shapes of the size and type of the objective component.
Material applied to objective shape with verified properties	4	Process has been modified to apply to objective shape
Material data properties verified	3	Process produces desired physical and mechanical properties
Material within family identified	2	Process has been applied to simple test coupons
Material family/families identified	1	General classes of possible processes identified

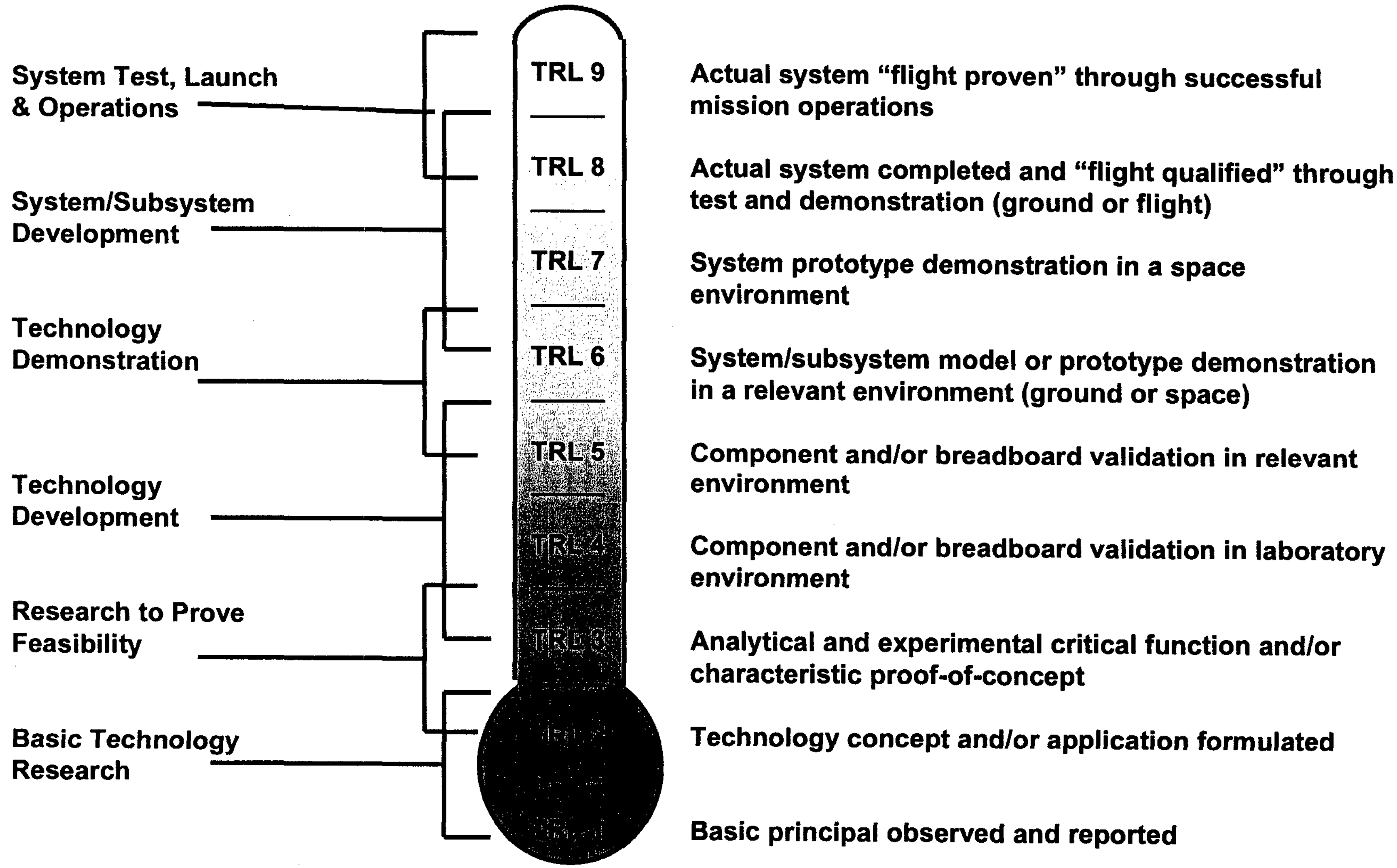
Reduced Pump Stages

- Historical engines typically have 2 or 3 stage pumps
  - SSME has 2 pumps for each fuel and oxidizer
  - relies on forged and machined Titanium
- To meet IHPRPT goals
  - reduce parts count
  - reduce complexity
  - remove a pump stage while increasing discharge pressure

Liquid Rockets Engines Face Great Materials Challenge



NASA Technical Readiness Levels



Full Flow Projects

- Nickel superalloy development
  - composition control for good oxygen compatibility and good structural performance
  - PM and casting process development

- Future potential projects
  - environmental barrier coatings development
  - nickel MMC

Increased Combustion Pressures

- Greater need for cooling (heat flux greater than 100 btu/in^{2}sec)
  - transpiration cooling
  - extreme temperature gradients (6000 °F combustion temperatures, cryo coolant)

Materials Requirements for Transpiration Cooling

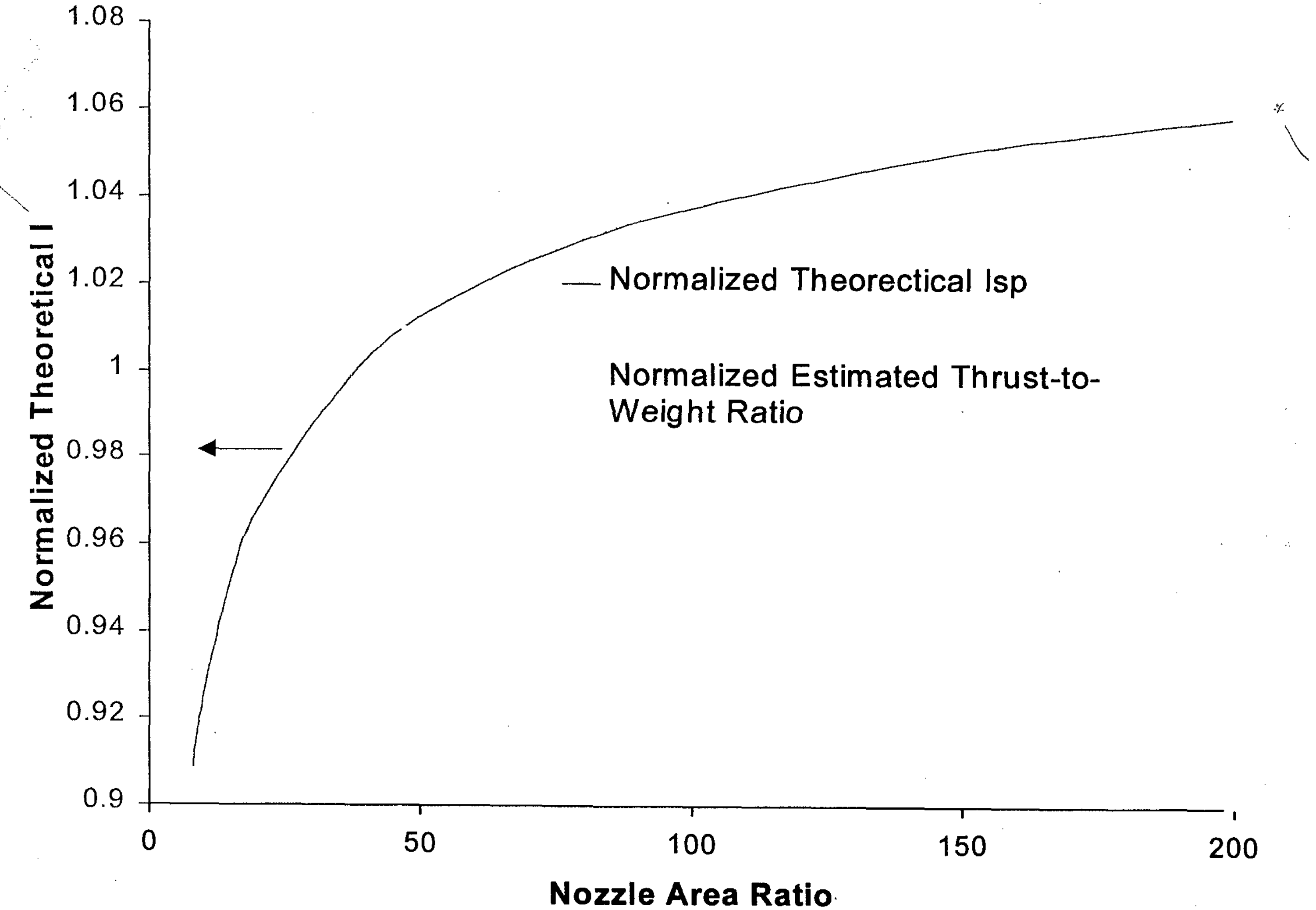
- Defined heat transfer rate
  - reliable structural performance at temperature with temperature gradient
- Controlled porosity
  - size of pores
  - density, density gradient
- Fabricatable into “hour-glass” shape (double curvature)

Higher Area Ratio Nozzles

- Ratio of throat area to exit plane area has a large influence on engine performance
- Influences engine weight with a practical size limit based on vehicle diameter

- Other Design Trades
  - amount of regenerative cooling
  - structural performance for side loads and gimbaling

Theoretical Engine Performance



Materials Requirements for Nozzles

- Resistance to chemical and thermal environment
  - actively or passively cooled
- "Reusability"
  - uncooled re-entry
  - replacement / repair
- Impermeability to exhaust gases
- Low density